Cognitive Radio test bed for optimized channel selection in IEEE 802.11-based networks

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ABSTRACT

In this paper, we describe a practical test bed and realization of distributed-sensing algorithm for optimized channel selection. The proposed method is tailored to the IEEE 802.11-based networks and could be highly beneficial for increasing efficiency and reliability of data communications with personal devices and in sensor networks deployed in challenging ISM band environments such as may be seen in hospitals and industrial settings. The test bed is being realized employing the CRC CORAL Cognitive Radio platform. The proposed algorithm for an optimized channel selection is based on a model that combines standard spectrum loading and channel use evaluation parameters, which allows fast and efficient selection of the most suitable channel for transmission. Moreover, the collected radio environment data from several sensing nodes could be stored for future real-time referencing in spectrum access decision making.

Categories and Subject Descriptors

C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Networks – *Access schemes.*

General Terms

Algorithms, Measurement, Design, Experimentation.

Keywords

Cognitive Radio, IEEE 802.11, distributed sensing, sensor networks, ISM band.

1. INTRODUCTION

In recent years the demand for wireless services was growing exponentially. Wireless users traditionally demand ubiquitous and reliable coverage with high data throughputs at longer distances from base stations or access points. This is especially critical for personal communications that call for high-bandwidth high-quality real-time transmissions and for sensor networks that demand high reliability and low latency with ubiquitous coverage of wider areas. On the other hand, users and operators have become increasingly price conscious, which in turn drove their attention to deployments using mass produced RF chip-sets available for devices in unlicensed bands, such as 2.4 GHz ISM band. However, all this brings to the unavoidable situation where high demand for unlicensed deployment of devices based on IEEE 802.11, as well as, other standards, results in overcrowding of the subject bands. This in turn results in a degradation of coverage of individual devices/networks, as well as, reducing effective bandwidth of transmissions. This situation is even more exacerbated in hospital and industrial environments, where communications networks may work side-by-side with the medical and industrial RF equipment that utilize the same ISM band.

In this paper we propose the practical and simple, yet sufficiently robust methodology for mitigating the effects of band overcrowding by means of Cognitive Radio (CR) techniques with distributed sensing of radio environment and well-informed choosing of operating channel that would be least prone to interference. It would be especially suitable for low cost designs such as, enhanced IEEE 802.11-based networks for personal devices and sensors in hospital and industrial environments with distributed set of Access Points (AP).

The main aim of the proposed algorithm is to perform a dynamic channel selection, based on estimating spectrum occupancy with sensing distributed across multiple AP nodes. This would allow creating smart CR Networks (CRN), consisting of hundreds of nodes that would communicate with each other to cooperate in building a comprehensive radio environment map database, which would be instrumental for autonomously selecting best channels across the network. Eventually, the database could be shared with external users to create a truly open co-operative environment for most efficient utilization of subject band. Although we focus our paper and developed test bed on the 2.4 GHz ISM band, the same method could be replicated in other unlicensed bands, most notably in the 5 GHz band.

The paper is structured as follows. In Section II we review the literature sources to establish the state of the art in dynamic channel selection for IEEE 802.11-based networks. Section III describes the proposed test bed made of CORAL CR platform and the algorithm for optimized channel selection. In Section IV we review the results of real-life testing of the proposed method. Finally, Section V offers conclusions and future research directions.

2. RELATED WORKS

Numerous proposals were made in the literature for optimized channel selection mechanisms in order to avoid interference, primarily with focus on intra-service emissions from neighboring nodes of the same type of systems. In this section we review some of the representative examples.

One of the mechanisms proposed in [1] is based on analyzing IEEE 802.11 traffic load on different channels. During the test phase, all available channels are being monitored by a device.

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Based on observed traffic and taking note of channel type (non-overlapping channels being preferential), the decision on choosing a particular channel is made. Significant attention is paid to the traffic type (UDP, TCP, etc.), because the particular protocol would allow predicting the degree and pattern of loading on that channel. However, the drawbacks of this method is that the observation time (20 min) is too long for most practical purposes, and moreover, the method does not maintain the history of previous measurements, which has negative impact on the efficiency of the following estimations.

Another proposal [2] develops a concept of improved airtime estimation based on user association, which takes into account various factors about channel status and average time for station to transmit single packet from an AP. This method has one drawback that airtime estimation requires extra time to send single frame in order to measure the channel overload. The authors proposed novel association scheme, which provided accurate status of the channel. Channel status is measured through two stages and only one of them includes sending packets. First, packets are being sent from the terminal equipment to AP, and then, in the next stage, the AP collects metrics for evaluation: error rate, average link rate, and packet size. However, to acquire these parameters the communication between AP and each new terminal seeking association is required. This means that the efficiency of the proposed algorithm is inversely linked to the number of users in the network.

Different approach is proposed in [3], where channel selection is based on the history of previous transmissions. This allows AP to predict the future transmissions on the channel, assuming quasi-stationary nature of channel parameters. Based on a result of packet transmissions, the scores are updated respectively for each possible outcome of transmission state: channel was busy, successful transmission, failed transmission. In order to relate the estimated traffic parameters to the history of transmissions "Bayesian" predictive model was used. Method assumes that channels are perfect and packet loss only happens when interference occurs, which in real environment scenario due to signal fading and possible LOS (line of sight) issue is not easily applicable for practical purposes.

Self-managing algorithm was proposed in [4], which does not require information exchange between different APs. Based on the feedback about detected interference on a given channel, the feasible solution to the channel allocation problem is derived. Since it is a self-managing channel selection method, it does not rely on any other information from the devices in the network and rely upon over-provisioning of channels while considering that nearby devices would not choose the same channel [4], thus each AP may have vulnerability to interference. This type of method could be reliable in scenarios where there are many available free channels and interference levels are not very high.

The identified problem with most previous approaches to dynamic channel selection is that they usually rely on just one method for measuring channel pollution/overloading. The proposal presented in this paper takes departure in the first two above described methods. However, the main difference is that the decision making takes into account the combination of parameters and is further reinforced by using cooperative sensing method, where the main device (central AP) will receive information from all network nodes (secondary APs). The collected information would be stored in the database for further re-use and will be easily referred to and manipulated as necessary for required calculations. Based on reports from cooperative sensing, there is an option to create not only self-aware network, but also a spectrum map of occupied and free channels that could be shared with other devices that are located in the operational area of the network.

3. PROPOSED TEST BED AND THE OPERATIONAL ALGORITHM

3.1 Cognitive Radio Test Bed

CR can be described as a smart radio that is very flexible and can adapt to any radio environment. According to concept creator – the CR is a device which can change its parameters accordingly to the information that is gathered from the environment [5]. CR devices work based on "Cognitive Cycle", which encompasses all the necessary procedures for selecting the best available frequency and using the spectrum opportunistically when needed, without causing harmful interference to primary users. CR topic has been now a subject of extensive research for the past several years, however, the practical prototypes and pilot networks only now started to appear on the market. Since IEEE 802.11-based networks are widely deployed and very popular for wide range of applications, they represent an attractive test case for employing CR methods for addressing the problem with the congestion of unlicensed ISM bands.

For testing our cooperative sensing and optimized channel selection algorithm, we have used the CR test bed implemented with the CRC's "CORAL" platform [6]. The CORAL was chosen as it is implementing a standard IEEE 802.11 chip-set with the CR-enabling features. It is possible to use one CORAL AP as central node for storing the radio environment data, collected by numerous network nodes – secondary APs, which can perform continuous radio environment monitoring without interrupting data transmissions. The main benefits of the cooperative sensing, essential for the task at hand are [7]:

1. Reduced probability of "hidden node" problems;
2. Better options to deal with SNR decrease;
3. Helping collection of real-time interference data without stopping transmissions;
4. More accurate information through comparing data from several nodes;
5. Larger sensing range.

It is of special noting that the proposed system is similar to the one established in IEEE 802.22 standard [8], which has similar working scenarios. As in IEEE 802.22, the proposed system can also operate in different modes which include: repeater, point-to-point and multipoint (mesh networks) scenarios. Furthermore, it can control the activity of all network node APs, such as, performing sensing and if needed reporting back about interference detection for incumbent user that was in a given channel before. Currently incumbent user detection in CORAL only uses MAC address detection. Since this is complicated and unreliable, the problem could be addressed by analyzing signal levels against a certain signal threshold limits.

The CORAL system is based on Mikrotik hardware with extra modifications to RF front-end. The system is composed of 5 distinct subsystems (see Figure 1). The first subsystem is the radio terminal itself, which uses IEEE 802.11 DCF protocol in order to establish link between AP and terminal stations.

It is being complemented by four other subsystems:

- Cognitive Radio Network Management System (CRNMS): performs all the necessary evaluation of received data, both from network nodes and the user;
- Control sensing protocol: used to get data from remotely located network nodes;
- Cognitive Engine (CE): used to control network behavior within its radio environment, providing adaptive intelligence;
- Radio Environment Awareness Map (REAM): allows storing all the information gathered by network nodes in one database.

CORAL APs also have a built-in GPS function for synchronization and location purposes.

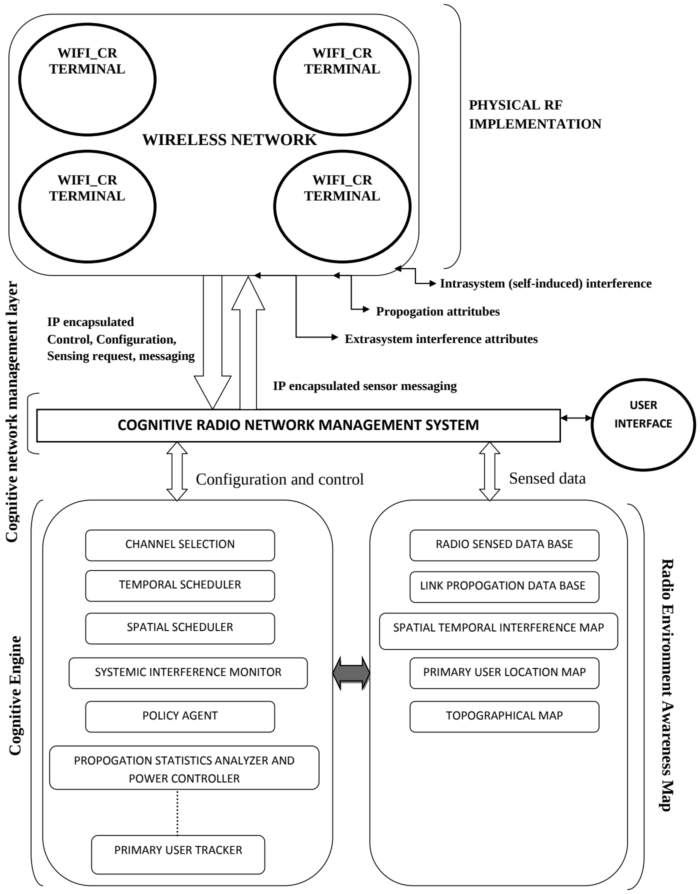


Figure 1. The block diagram of CORAL CR test bed [6]

Radio environment monitoring at CORAL network nodes is performed by using dedicated secondary receivers which have detection threshold of -100dBm/MHz. Thanks to flexible software complement, it is possible to perform all kinds of manipulations and analysis of the data collected in the REAM from all network nodes.

The primary analysis is performed by using a built-in spectrum analyzer [6]. Spectrum analyzer forwards 101 bins of power values from 2400 MHz to 2500 MHz to the main Ethernet Buffer Board (EBB), where data is processed when terminal is not transmitting. Based on the scanned spectrum data, the minimum, maximum and average values in dBm are calculated for different channels. Results are stored in a buffer. The same operation is repeated for the next data using an alternative buffer. Spectrum analysis could be performed both at the AP, as well as, at any terminal station. Based on acquired results, the CRNMS can display spectrum graph at any given point as in example given in Fig. 2.

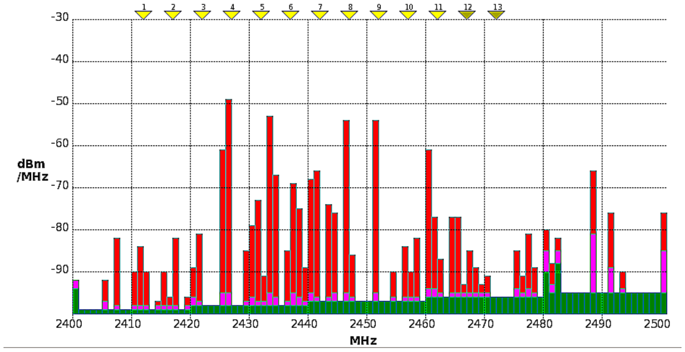


Fig. 2. Example of 2.4 GHz spectrum scan by CORAL

Of a particular importance to operation of the proposed channel selection algorithm is the CORAL's REAM database. It stores the values of following parameters that all can be used for optimized channel selection:

1. Sensor MAC address;
2. Source Address of Packet;
3. Destination Address;
4. Measured RSSI value;
5. Channel Utilization;
6. BSSID;
7. Channel #;
8. SSID;
9. Time stamp of when data was acquired;
10. "$U_{seconds}$" - time period from last seen packets.

As can be seen, the CORAL system not only detects other network devices from central AP, but also monitors other (terminal) nodes, which helps to determine usage of the entire range of different channels.

3.2 Proposed channel selection algorithm

Based on the literature review presented in Section 2, we propose a practical channel selection algorithm which is oriented to analysis of a historical measurement data, rather than predictions as proposed in [3]. This allows making full use of distributed sensing metrics collected in the network such as that acquired by CORAL-based test bed. Similar method of relying on historical channel measurements data is used in commercial IEEE 802.11 devices (such as, made by Ubiquity, Motorola, Deliberant and others), however, the main difference is that our method uses cooperative spectrum sensing from APs and terminal devices, whereas current commercial systems only use data collected by a given AP.

We propose the algorithm for deciding the best channel from the combined analysis of the following parameters: RSSI (Received signal strength), Utilization, "Channel", "$U_{seconds}$". We also propose taking into account an additional factor of channel overlapping (W), which is a common metric in 2.4 GHz band. This factor also applies to 5 GHz band, so it is important to have this variable as a part of the equation, because usually wireless service providers use wider than 20 MHz channels leading to channel overlapping and suffering from adjacent channel interference.

The proposed equation for expressing the channel preference factor *B*:

$$B = \frac{\left(\frac{1}{n}\sum_{i=0}^{n} R_i\right) + \left(\frac{1}{1000}\cdot\left(\frac{1}{n}\cdot\sum_{i=0}^{n} P_i\right) + W\right) + S}{T} \quad (1)$$

Where:

n – number of sensing nodes,

S – number of identified APs and terminals using the channel,

R_i – RSSI value observed on specified channel by "CORAL" sensing node *i*.

P_i – total number of packets observed in the channel by sensing node *i*,

W – channel overlapping factor,

T – time since the last packets had been seen at the sensing nodes.

The second summation derives arithmetical mean for the total number of observed packets on monitored channels. If channel is overlapping, which is common in the 2.4 GHz band, then *W* factor will have impact on the decision, by taking into account the packets on the overlapping channels, otherwise W = 0 is selected. Note that the average packet number is divided by 1000 in order to get the normalized factor reflecting the packet traffic, rather than absolute number of packets observed in a given channel.

The factor *B* is to be calculated for all channels used/observed by the CRN and the channel receiving the smallest *B* score would be judged as the least occupied and most optimal choice for transmission.

4. EXPERIMENTAL RESULTS

4.1 Testing set-up

The overall physical set-up of the experimental test bed for the initial testing of the proposed concept is depicted in Figure 3 below.

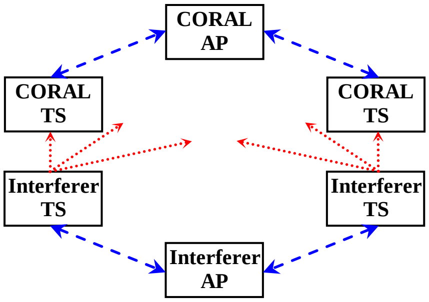


Figure 3. Testing set-up

Testing was performed in indoor environment (one of university rooms, size 6 x 6.8 x 5 m). CRN was modeled by CORAL AP with two associated Terminal Stations (TS), all of which had full sensing capability. The distance from AP and TS was accordingly, 2 and 4 meters.

Along with the usual busy 2.4 GHz spectrum typical of a city centre university building (as illustrated in Fig. 2, this includes signals from university WiFi network and local offices APs in the same building), in order to create more suitable interference scenario reminiscent of harsh ISM environment, three additional devices where installed within direct proximity (1 m) of the CRN devices and used for generating high levels of interference on a given channel. These are shown in Fig. 3 as Interferer AP and two TSs. These interferers were implemented using commercial IEEE 802.11 devices "APC 2Mi" (working as AP), as well as, "APC 2M-8" and "APC 2S" (working as TSs). Although, these devices are capable of working as standard IEEE 802.11 b/g/n devices, they were programmed to use a proprietary protocol for communicating among themselves using "token ring" principle in order to establish uninterruptable stream with high interference potential.

In such a manner the interferers were made to represent the worst case noisy ISM devices, which could be met in the everyday environment of industrial factory or hospital.

In order to generate traffic between all these devices, the network traffic generator "Nepim" tool was used. The following settings were applied to interferer system:

- 20 MHz channel width, using channel 11 (2462 MHz);
- 10 dBm transmit power.

The equation (1) was implemented in the test bed using CORAL's Python API, however, it also can be implemented by using Matlab or C/C++ code.

The evaluation of channel preference factor was performed in the following sequence:

1. Every 60s REAM database was updated with information from the wireless network nodes;

2. The 40 latest measurement results were used for estimating *B* for every channel;

3. In order to compare detected network nodes, additional scanning was performed by using *iwconfig ath0* scan on a CORAL system;

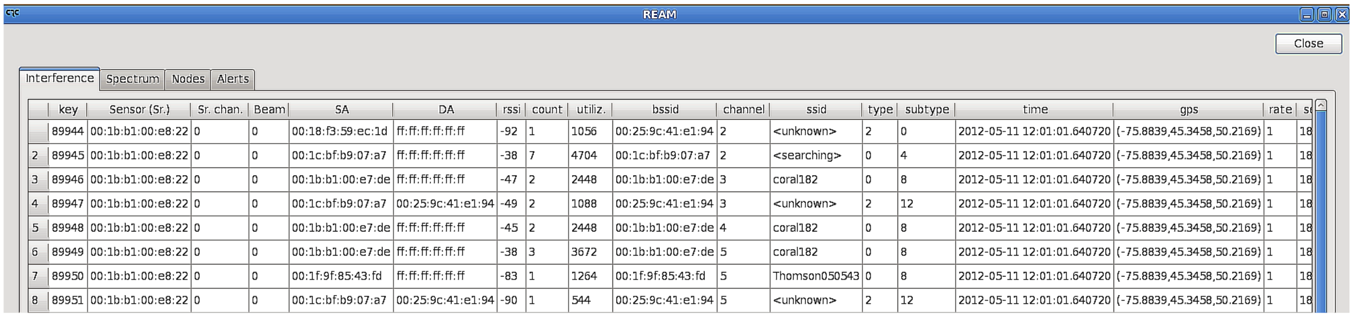
4. Detected network devices were determined for each channel, the total number reported back to management software client;

5. The channel preference factor *B* was calculated by using the equation (1). After calculating *B* for all channels, the best channel was selected based on the lowest measured score.

4.2 Measurement results

All networked devices were operating at optimal receive signal levels between -35 and -42 dBm.

While constant bit stream passed between the nodes of interfering network, the CRN prototype test bed operated in a normal mode with distributed monitoring, with all the collected data being stored in the REAM database. The measurement time and parameters settings were controlled by using CORAL's Python API. This API allows changing the measuring time (Polling interval) with the other parameters such as, transmit power, channel width, channel frequency, monitoring channel, beam scan mode. An example of REAM GUI with a snapshot of the gathered data is shown below in Figure 4.



	key	Sensor (Sr.)	Sr. chan.	Beam	SA	DA	rssi	count	utiliz.	bssid	channel	ssid	type	subtype	time	gps	rate	se
	89944	00:1b:b1:00:e8:22	0	0	00:18:f3:59:ec:1d	ff:ff:ff:ff:ff:ff	-92	1	1056	00:25:9c:41:e1:94	2	<unknown>	2	0	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
2	89945	00:1b:b1:00:e8:22	0	0	00:1c:bf:b9:07:a7	ff:ff:ff:ff:ff:ff	-38	7	4704	00:1c:bf:b9:07:a7	2	<searching>	0	4	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
3	89946	00:1b:b1:00:e8:22	0	0	00:1b:b1:00:e7:de	ff:ff:ff:ff:ff:ff	-47	2	2448	00:1b:b1:00:e7:de	3	coral182	0	8	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
4	89947	00:1b:b1:00:e8:22	0	0	00:1c:bf:b9:07:a7	00:25:9c:41:e1:94	-49	2	1088	00:25:9c:41:e1:94	3	<unknown>	2	12	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
5	89948	00:1b:b1:00:e8:22	0	0	00:1b:b1:00:e7:de	ff:ff:ff:ff:ff:ff	-45	2	2448	00:1b:b1:00:e7:de	4	coral182	0	8	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
6	89949	00:1b:b1:00:e8:22	0	0	00:1b:b1:00:e7:de	ff:ff:ff:ff:ff:ff	-38	3	3672	00:1b:b1:00:e7:de	5	coral182	0	8	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
7	89950	00:1b:b1:00:e8:22	0	0	00:1f:9f:85:43:fd	ff:ff:ff:ff:ff:ff	-83	1	1264	00:1f:9f:85:43:fd	5	Thomson050543	0	8	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18
8	89951	00:1b:b1:00:e8:22	0	0	00:1c:bf:b9:07:a7	00:25:9c:41:e1:94	-90	1	544	00:25:9c:41:e1:94	5	<unknown>	2	12	2012-05-11 12:01:01.640720	(-75.8839,45.3458,50.2169)	1	18

Figure 4: Example of REAM GUI

An example of the data extracted from REAM for further processing in Eq. (1) is shown below in Table 1.

Table 1. Example snapshot of REAM data values

RSSI	Utilization	SSID	Channel	$U_{seconds}$
-39	**2448**	coral182	5	**856660**
-77	**6320**	thomson	6	**252606**
-50	**3672**	coral182	6	**265466**
-93	**12800**	VRM	6	**294892**
-50	**2408**	unknown	6	**295949**
-65	**109**	unknown	6	**296020**
-56	**9312**	AndroidAP	6	**333405**
-71	**5056**	Thomson	7	**764571**
-51	**11640**	AndroidAP	7	**845431**
-34	**1728**	test	7	**244961**

Based on "REAM DB" data in Utilization and Channel columns, an example of channel occupancy visualization is provided in Figure 5.

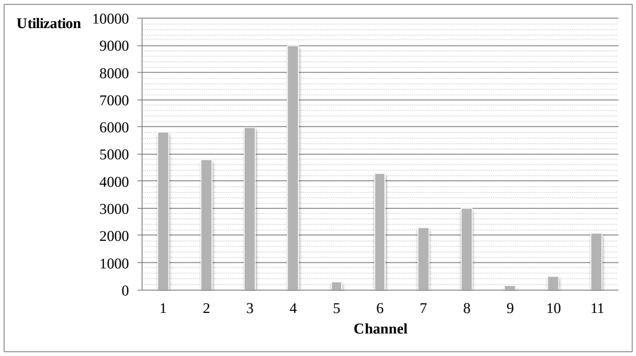


Figure 5: Example of channel occupancy measurement

In order to estimate the efficiency of the proposed channel selection algorithm on the realized CRN test bed, we carried out comparative measurements in real time. The period of polling remote terminals for sensing information was set to 60 seconds (any shorter time frame would require more CPU cycles, which would have negative impact on the overall performance of device).

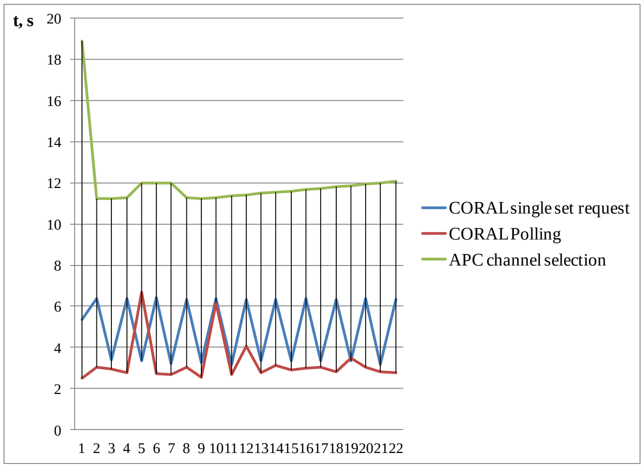


Figure 6. Test bed CRN channel selection performance when using different spectrum data capture methods

Depending on the polling delay (or if using a single request of data sets from CRN nodes without enabling cyclic polling) and the amount of data that is gathered from CRN nodes for storing at the REAM database, the realized CRN test bed was able to settle on the most optimal channel within 5…15 seconds, as may be seen in Fig. 6 above, observed over 20 measurements. This is much faster than any of the previously proposed methods. Moreover, because of employing the cooperative sensing, the channel selection input data is more accurate and can provide more details without the cost of reducing speed of channel selection. As a positive side effect of storing and processing historical measurement data in the REAM database, it can be possible to perform instant optimal channel selection with simple look-up in the REAM database, i.e. without additional polling of all remote CRN nodes. Below Figures 7 and 8 show the comparison of channel selection performance of respectively the realized CRN test bed vis-à-vis a reference state-of-the-art commercial IEEE 802.11 system Deliberant APC 2Mi. The y-coordinate in the figures indicate the coefficient that shows normalized occupancy value for each channel based on an algorithm used by respective systems. It can be seen that during 5 measurements different channels were selected on "Commercial" and "CORAL" systems, with CORAL test bed consistently outperforming the commercial systems by obtaining lower channel occupancy values.

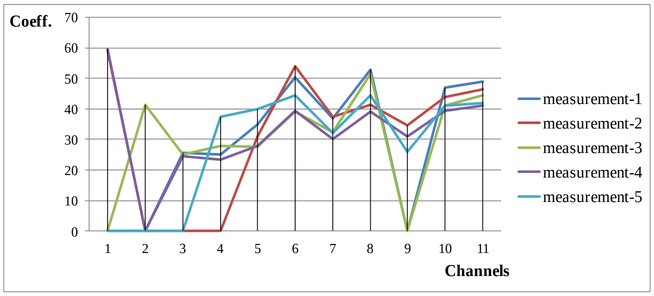


Figure 7. Test bed CRN channel selection graph

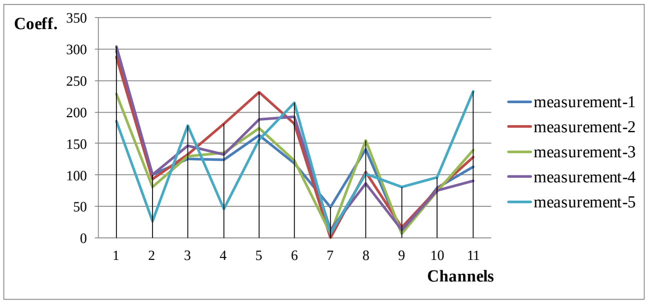


Figure 8. Commercial device channel selection graph

Performed tests show that using historical measurement data and distributed sensing enables CRN to select better channel much faster. In contrast, the commercial state-of-the-art IEEE 802.11 devices perform scans less then 30 s, which does not give a broad view about the channel occupancy.

The functioning of the proposed method also compares favorably with previously proposed channel selection methods that rely on “single-metric” such as, the one proposed in [2], where the system evaluates channel occupancy by a number of successfully sent packets per channel, overlooking other factors such as, distance between AP and TS, which has significant impact on signal levels and error rate. So for instance, while channel can appear nominally free, the larger link distance will result in lower average data rate and higher error rate and because of this, the channel will be discounted as not suitable for AP transmission. However, actually, for shorter link distances given channel might be perfectly suitable. Our proposed multi-factor method allows much more nuanced decision making by taking into account additional important factors such as RSSI levels and total number of APs and TSs.

Differently than other analyzed approaches, the proposed optimized channel selection algorithm can be very effective for point-to-point (PP) link scenarios, where cooperative sensing – both from master and slave sides, would let to determine most optimal channel. Placing few PPs would allow creating extensive REAM, which could help to examine channel occupancy and interference dynamics at a long range links.

5. CONCLUSIONS

In this paper we proposed a practical CRN test bed implementation with the algorithm for channel selection optimization based on a cooperative network sensing. The proposed CRN operational scenario was modeled in realistic conditions with heavy interference sources typical of hospital, industrial and similar ISM environments and showed that:

Proposed method allows real time processing of sensing data in high interference environments. Using channel optimization algorithm, the look-up priority list of candidate channels could be created and used for dynamic channel selection by the subject system, and also provided as a reference to other neighboring users of the subject band.

The experimentally confirmed speed of dynamic channel estimation and selection compares favorably with that attainable by commercial IEEE 802.11 systems and the previously proposed algorithms. If requesting only one data set from sensing nodes, the sub-optimal channel selection can be nearly instant.

The use of cooperative sensing not only allows minimizing hidden node problems, but also provides more substantial metrics from across the entire set of CRN nodes, which can be used in order to create more detailed radio awareness maps, determine spectrum holes or optimize performance by using fair allocation of the channels.

The proposed method and its practical testing confirmed the notion that RSSI is not always the main factor that determines the decision. It was shown that in some cases the complementary derivative activity factors, such as the amount of traffic (i.e. number of packets) observed on a given channel, become a more important element in decision making of the optimal channel.

Considering these findings, our future research shall consider the practical testing with the larger number of CRN nodes and interferers, as well as the consideration of how the design of channel selection algorithm could be made more robust in identifying “hidden nodes”, e.g. through refined analysis of the RSSI component.

6. ACKNOWLEDGMENTS

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